Critical defect size on the extreme ultraviolet (EUV) mask and cleaning process for its removal

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Outline

01 Introduction

02 Research Objective

03 Experimental Procedure

04 Results and Discussion

- Critical defect size on 16 nm EUVL mask
- Ultra fine particle removal by megasonic cleaning

05 Summary

Introduction

Scaling Scenario : Lithography

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
MPU	32nm	22nm				16nm				11nm	
Logic	32nm		22nm				16nm			11nm	
DRAM	2Xnm			2Ynm / 1Xnm				1Ynm or Emerging Memory			
NAND	2Xnm		1Xnm		1Ynm or 3D		3D		3D or New		

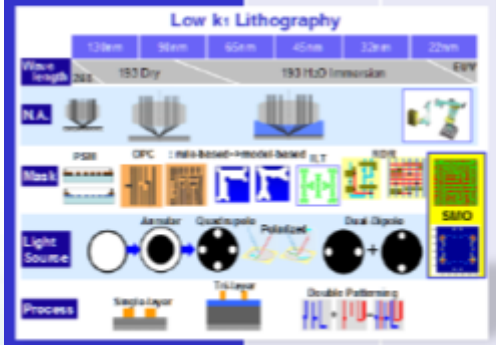
Technology

ArF Immersion

ArF Immersion
DP(SADP, LELE, LLE), NTD, SMO

*DP Double Patterning
*SADP Self-Aligned Double Patterning
*LELE Litho Etch Litho Etch
*LLE Litho Litho Etch
*NTD Negative Tone Development
*SMO Source and Mask Optimization
*MP Multiple Patterning

ArF Immersion Low-k1 Lithography
DP Multiple SADP(1/4) , Spacer & Cut



EUV Lithography

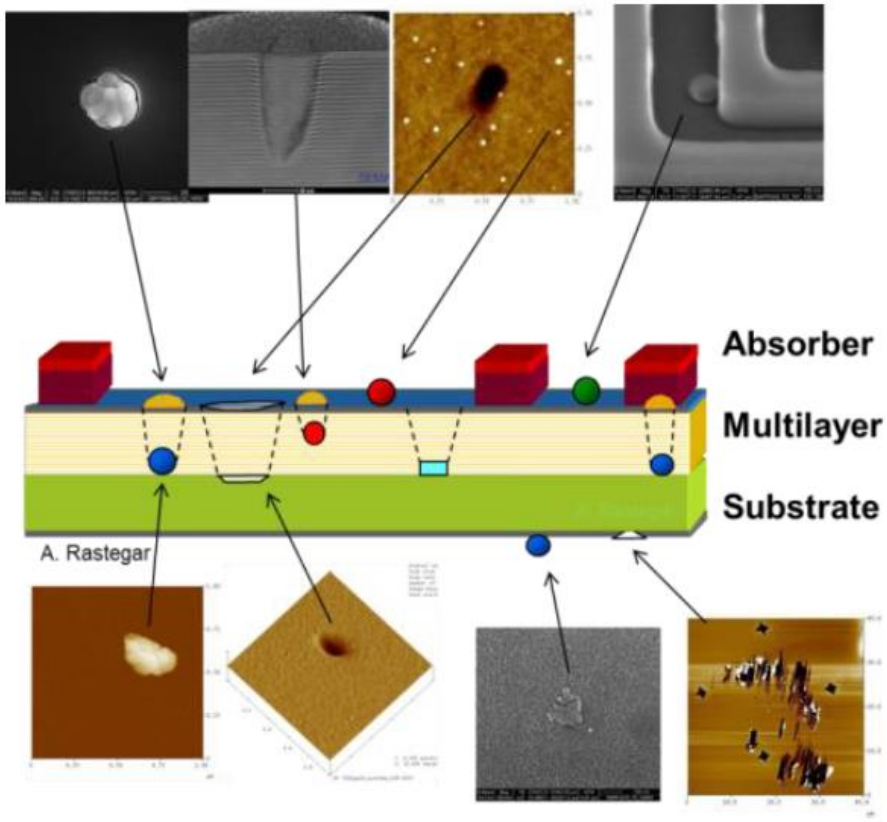
EUV Extended (DP…)

Direct Writing / EB, Nano Imprint
& Directed Self Assembly

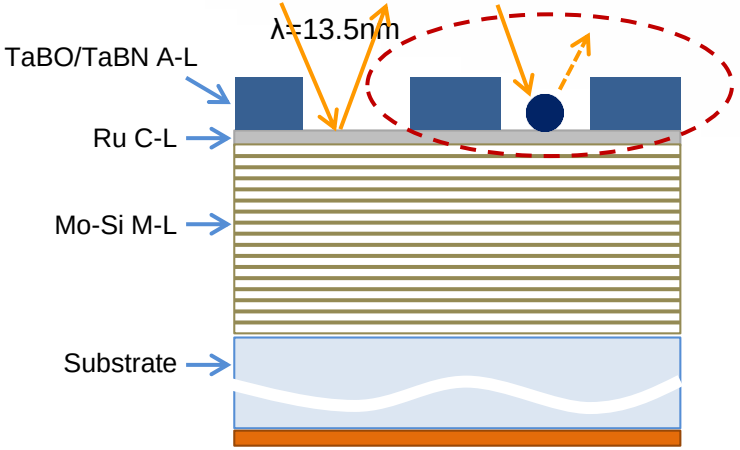
G. Chung, “Partnership to build a better future, and leading edge collaboration”, SPCC (2012)

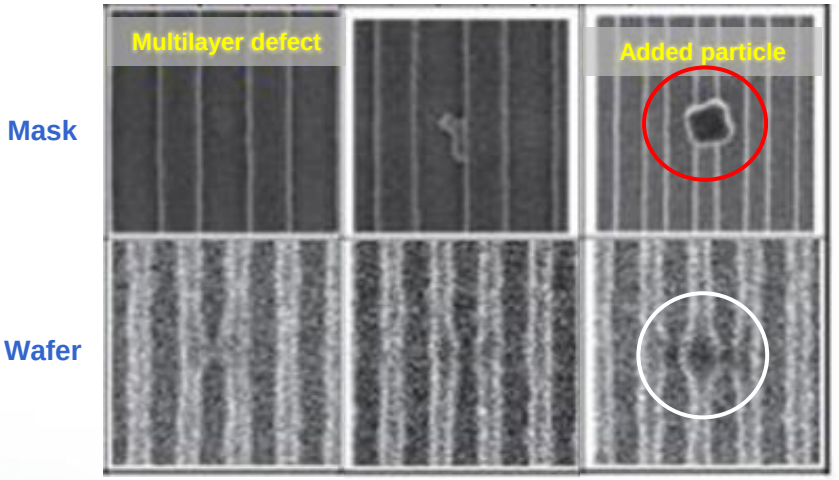
Issue of contaminated particles on EUV mask

❖ EUV mask defects



❖ Effect of contaminated particle

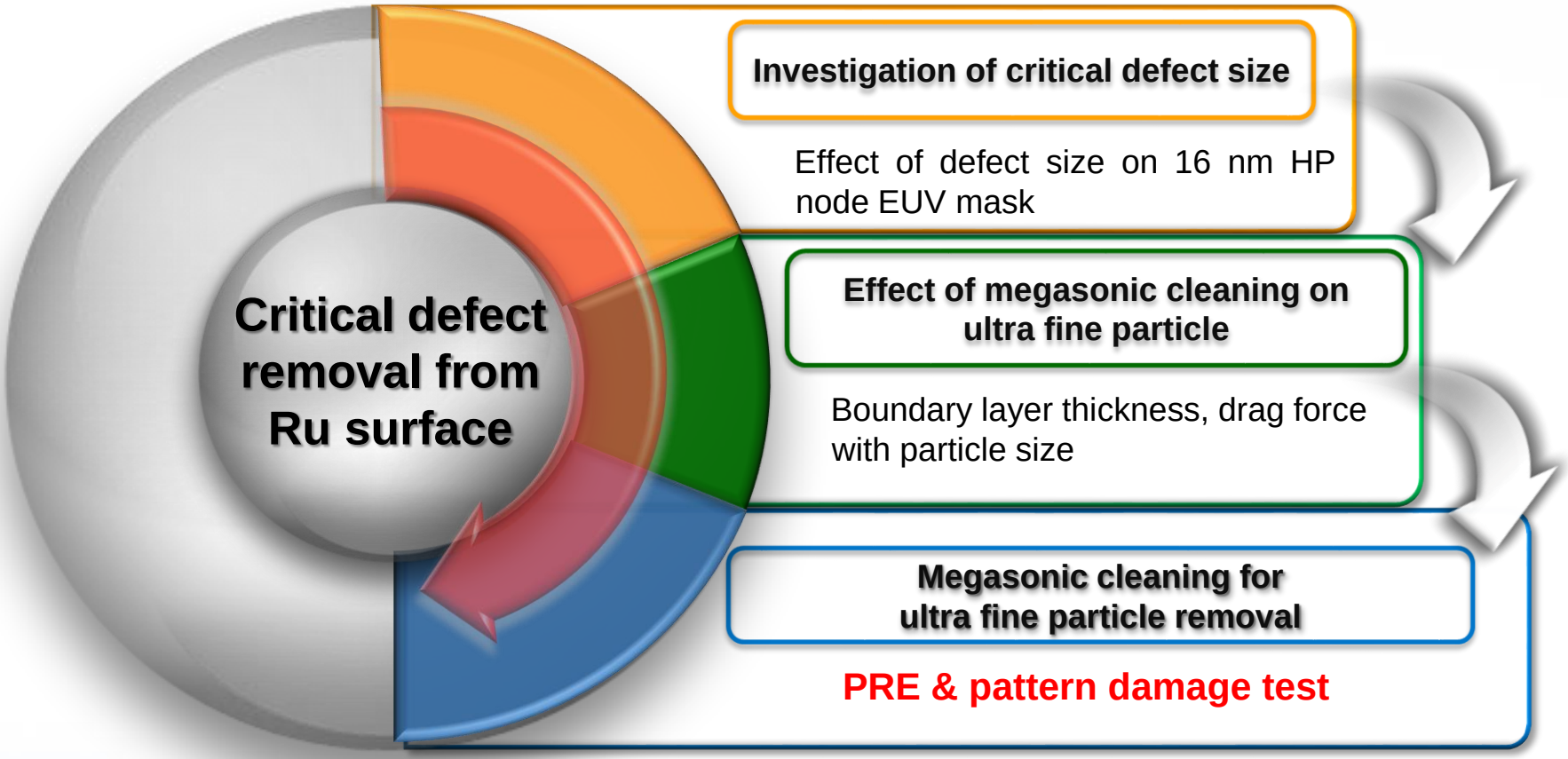




Fine particles on EUV mask can be printed !!

→ Particles should be removed without damage on EUV mask

Research Objective



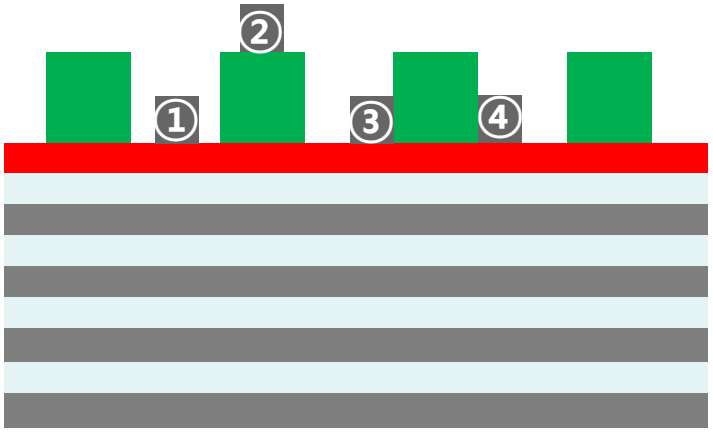
Critical defect size on EUV mask

Experimental procedure [Critical defect size]

❖ Conditions

Wavelength	13.5 nm
Illumination	Dipole
Coherence (σ_r_σ_c)	0.1_0.8
Numerical Aperture	0.33
Target CD (at wafer)	16 nm
Target CD (at mask)	64 nm
Reduction (Mask : wafer)	4:1

❖ Position of defect on EUV mask

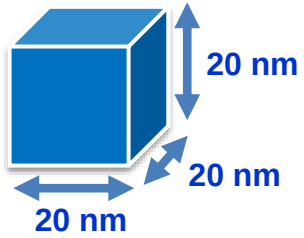


① Space b/w absorber pattern
② On the absorber pattern
③ Left side of absorber pattern
④ Right side of absorber pattern

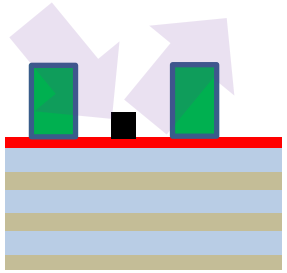
❖ Defect materials

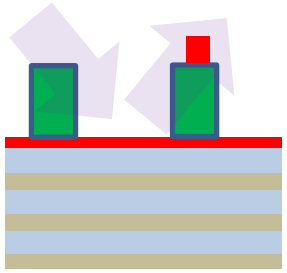
Sn / TaN / W / SiO_2 / C

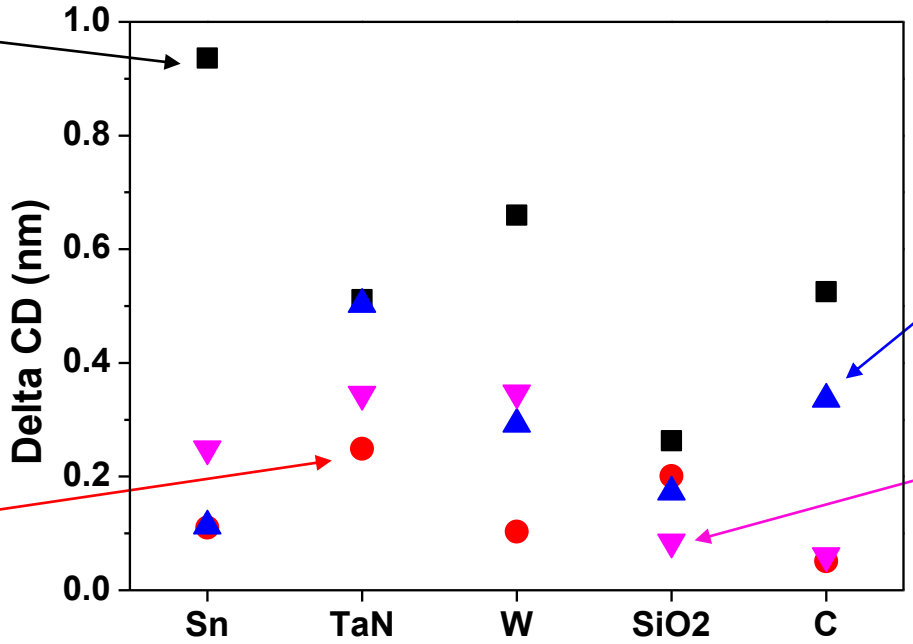
CD variation w/ defect position

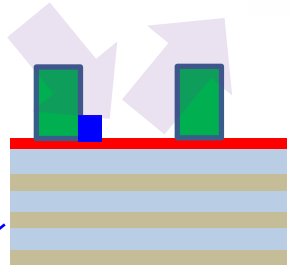


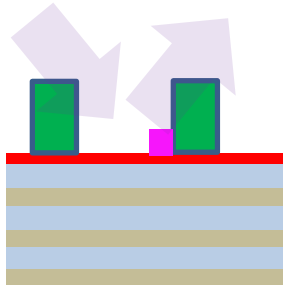
(Defect size : 20 nm)


Space


Absorber



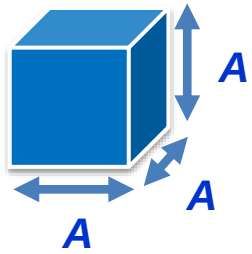

Right side


Left side

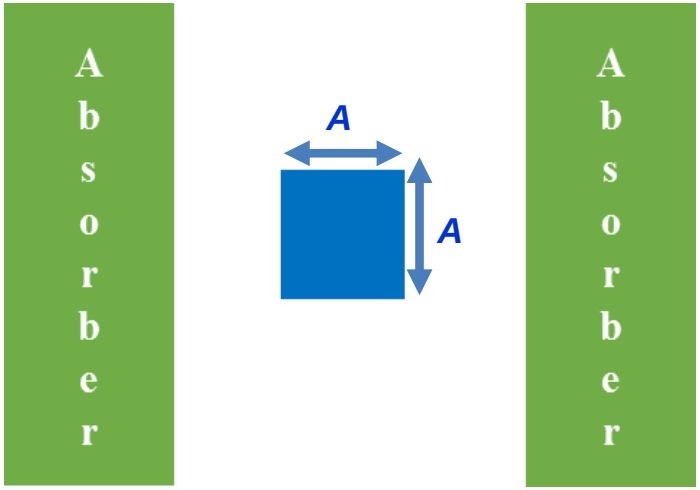
- **CD variation w/ defect position**

 → **Space > Right side > Left side > Absorber**

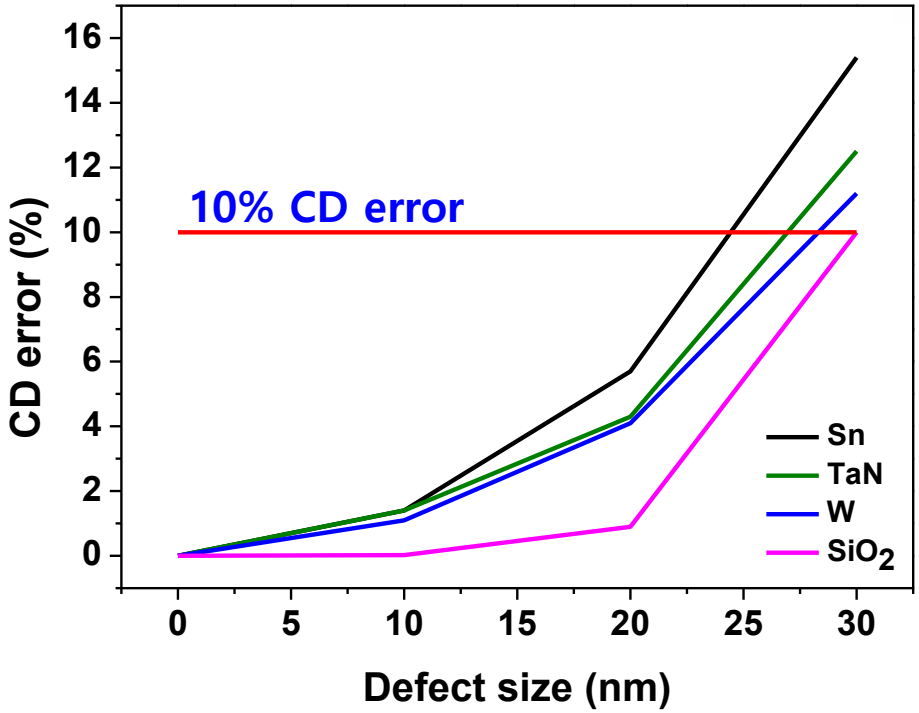
CD variation w/ defect size



A = Defect size



Defect in space

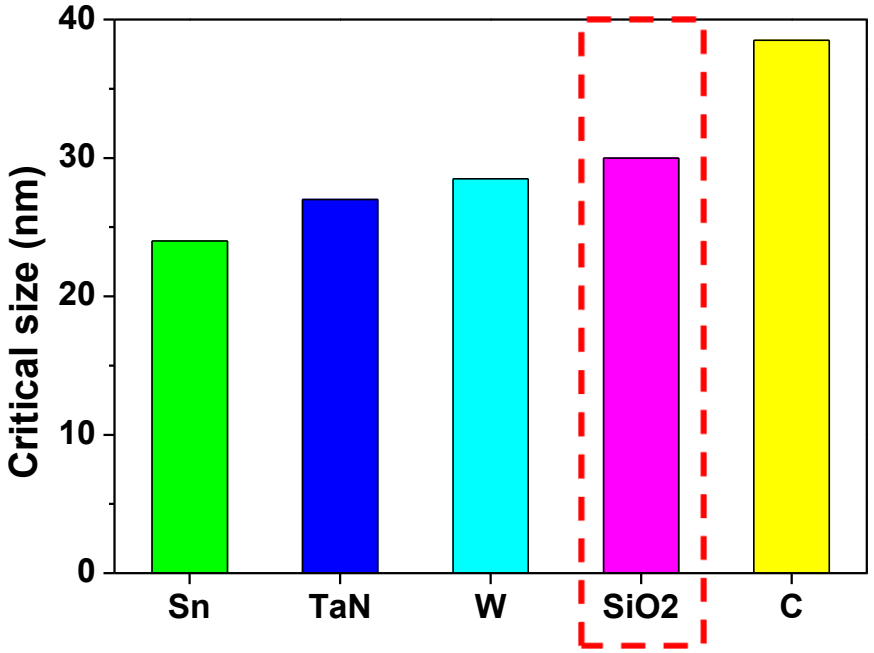


- Critical defect → 10 % CD error
- CD error is drastically increased with increasing defect size

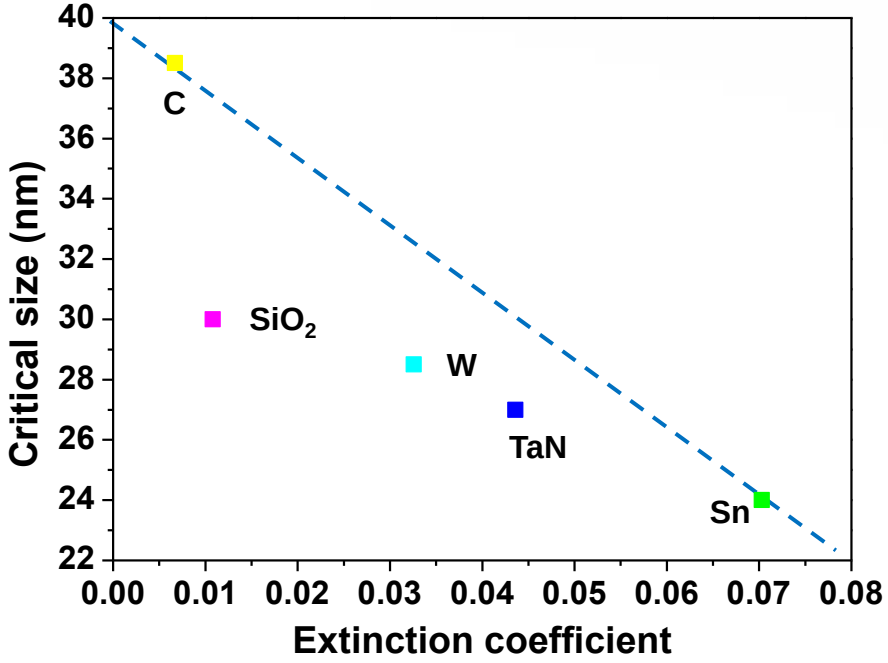
 → Sn > TaN > W > SiO_2

Relationship b/w critical size & extinction coefficient

❖ Critical size w/ various materials



❖ Extinction coefficient



- Critical defect size is in inverse proportion to extinction coefficient
- 10 % CD error caused by 23 nm ~30 nm particles @ 16 nm HP node EUV mask

 → Below 30 nm particles should be removed

➢ Cleaning process is required to remove ultra fine particles

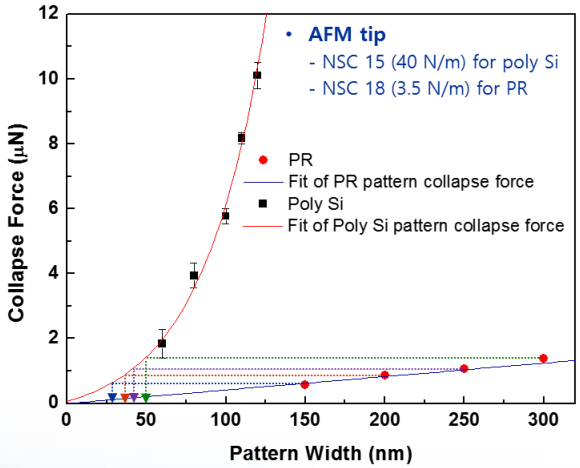
Megasonic cleaning for 30 nm particle removal

Experimental procedure [Cleaning test]

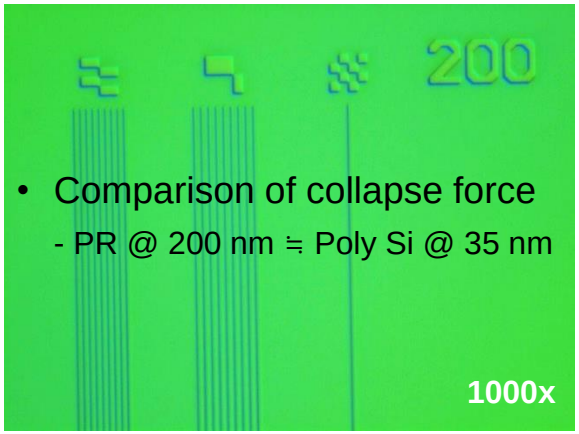
❖ Particle removal & pattern damage test w/ megasonic cleaning

Sample preparation	Megasonic cleaning	Evaluation of PRE & pattern damage
- Standard silica particles (30, 137 nm) - 2 cm X 2 cm Ru wafer - Wet deposition & 1day aged - PR line pattern (200 nm)	- 1, 2 MHz megasonic (Durasonic, Korea) → MS power ~ 10 W → Cleaning time ~ 30 sec - DIW, dNH_4OH (pH10), H_2-DIW (1 ppm)	- Optical Microscope (LV100D, Nikon, Japan) → For 137 nm silica particle & pattern damage - AFM (XE-100, Parksystem, Korea) → For 30 nm silica particle

❖ PR vs Poly Si pattern collapse force



❖ OM image of PR pattern 200 nm

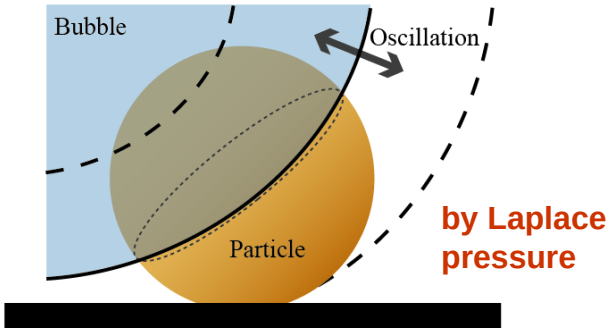


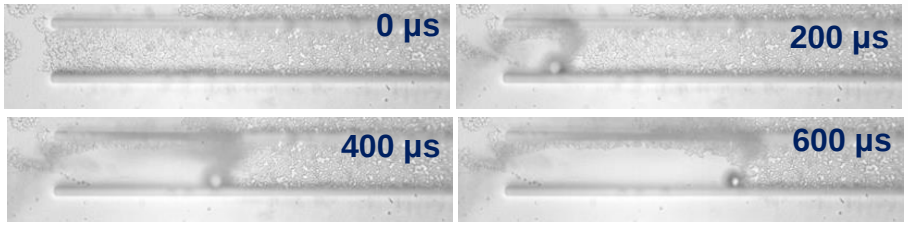
- Pattern collapse force were measured to justify the deviation between PR and Poly Si pattern

➔ **Evaluation of pattern damage by MS cleaning**

Mechanism of Megasonic Cleaning

❖ Bubble oscillation + microstreaming **(stable cavitation)**



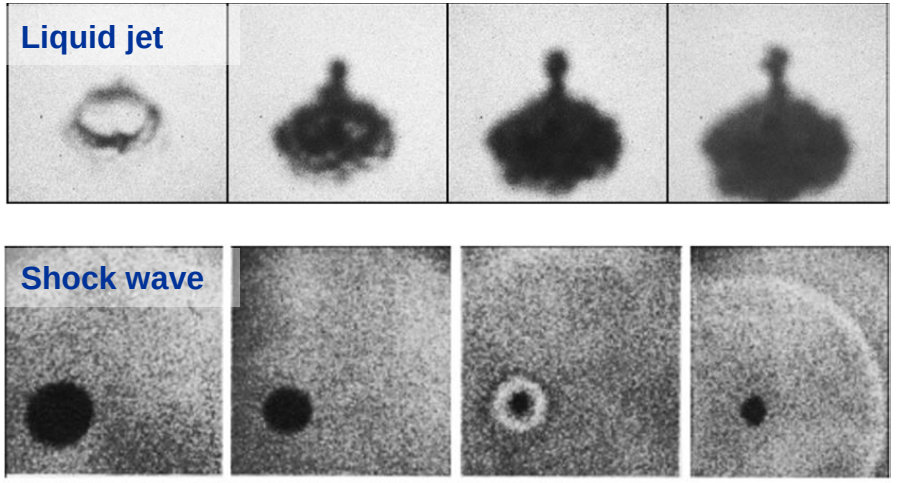


W, Kim et al., *Applied Physics Letters*, **94**, 081908 (2009)

Particles could be removed by the force induced bubble oscillation with microstreaming

❖ Bubble collapse **(transient cavitation)**





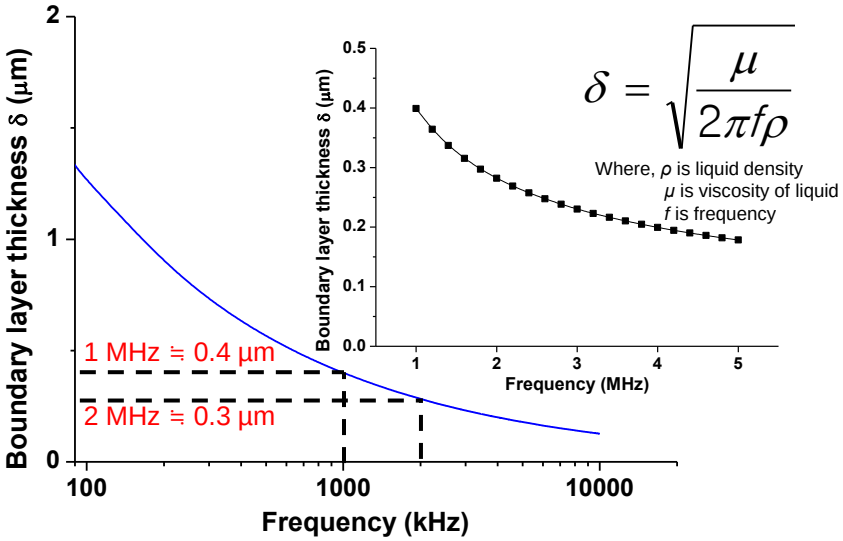
H. Tomita et al., *Solid State Phenomena*, **145-146**, 3-6 (2009)

- **When bubble collapse, it cause liquid jet or shock wave**

 ➔ **Removal of contaminated particles and generation of pattern damage**

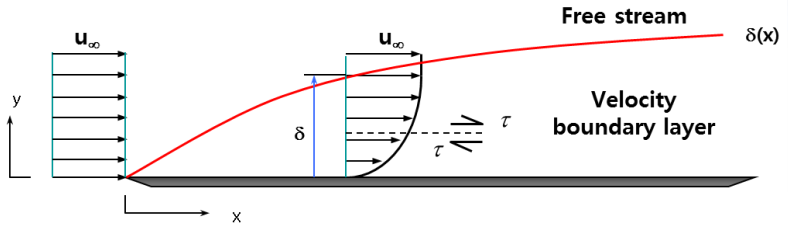
Boundary layer thickness in acoustic filed

❖ Boundary layer thickness in ultrasound field



$$\delta = \sqrt{\frac{\mu}{2\pi f \rho}}$$

Where, ρ is liquid density
μ is viscosity of liquid
f is frequency



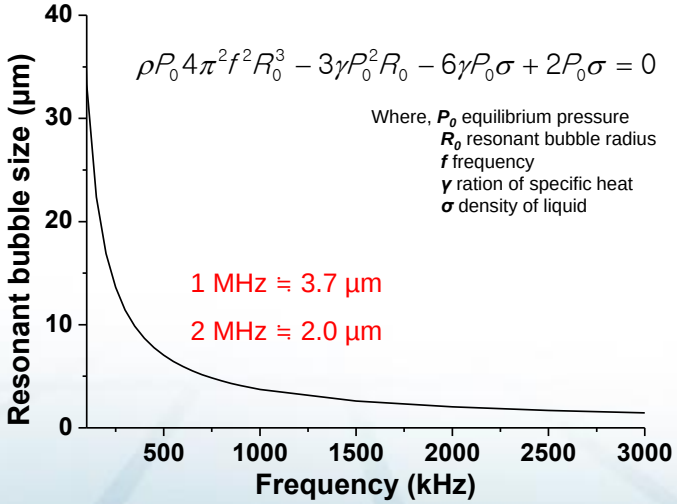
Velocity boundary layer on a flat plate

$$\delta(x) = 5\sqrt{\frac{\nu x}{U_\infty}}$$

Where, ν is kinematic viscosity
U_∞ is velocity of outer flow
x is position

H. Schlichting and K. Gersten, *Boundary layer theory*, 8th Ed., Springer (2000)

❖ Resonant bubble size @ frequency

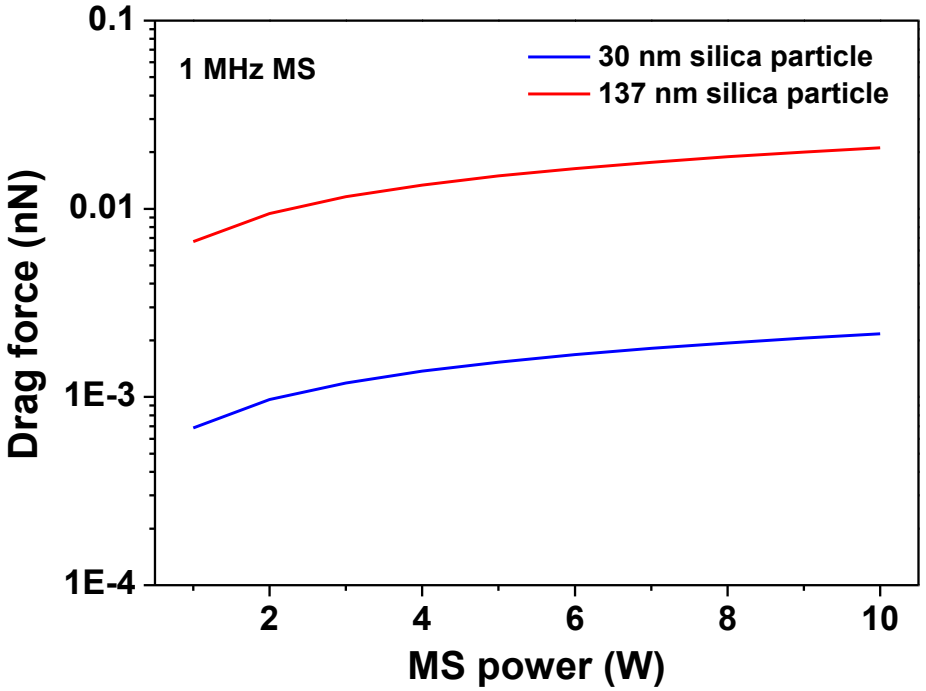


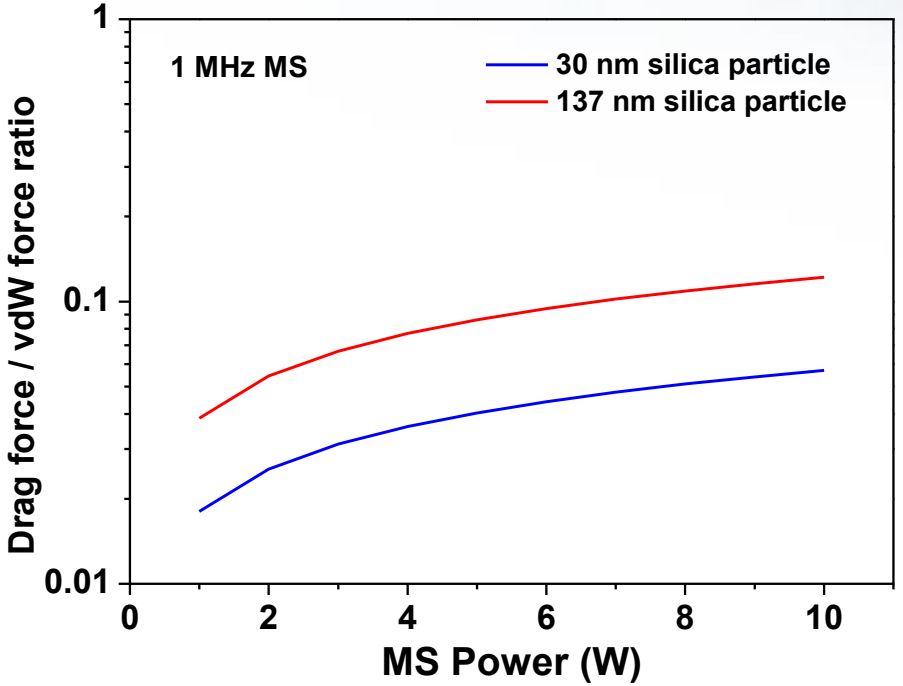
$$\rho P_0 4\pi^2 f^2 R_0^3 - 3\gamma P_0^2 R_0 - 6\gamma P_0 \sigma + 2P_0\sigma = 0$$

Where, P_0 equilibrium pressure
R_0 resonant bubble radius
f frequency
γ ration of specific heat
σ density of liquid

- **Boundary layer thickness is decreased with increasing frequency in acoustic field**
 - → **High freq. is more effective to remove small particles**
- **Resonant bubble size is also decreased**
 - → **Bubble collapse force would be decreased**
- **Boundary layer thickness grows in proportion to $x^{1/2}$**

Drag force on particles by fluid flow





- **Instantaneous fluid particle velocity**

$$u = \sqrt{\frac{I}{\rho c}}$$

Where, I is intensity of incident acoustic waves
μ is viscosity of liquid
f is frequency

Q. Qui and G. J. Brereton, IEEE Trans. Ultrason., Ferroelect., Freq. Control, ***42*** (4), 1995

- **Drag force on the particles**

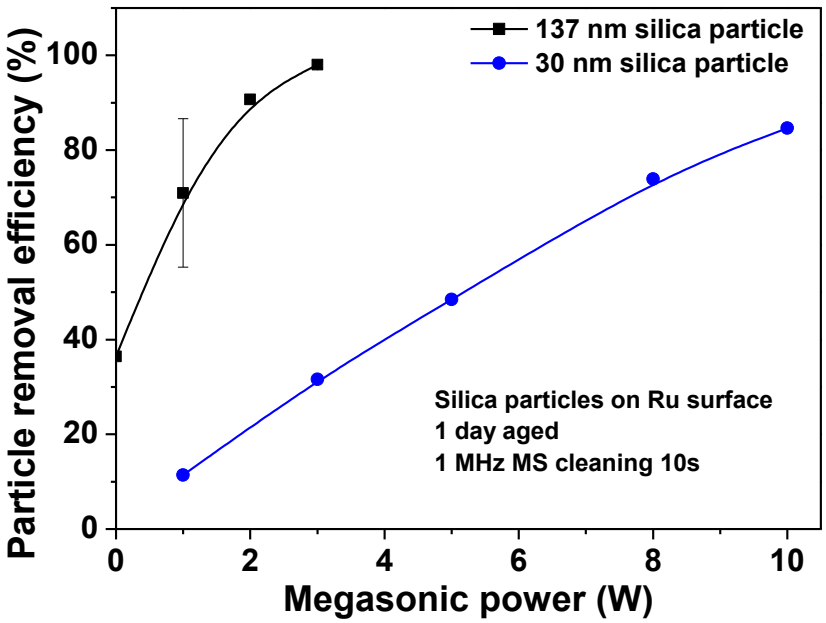
$$F_D = 1.7009 \cdot (3\pi\mu d V_p)$$

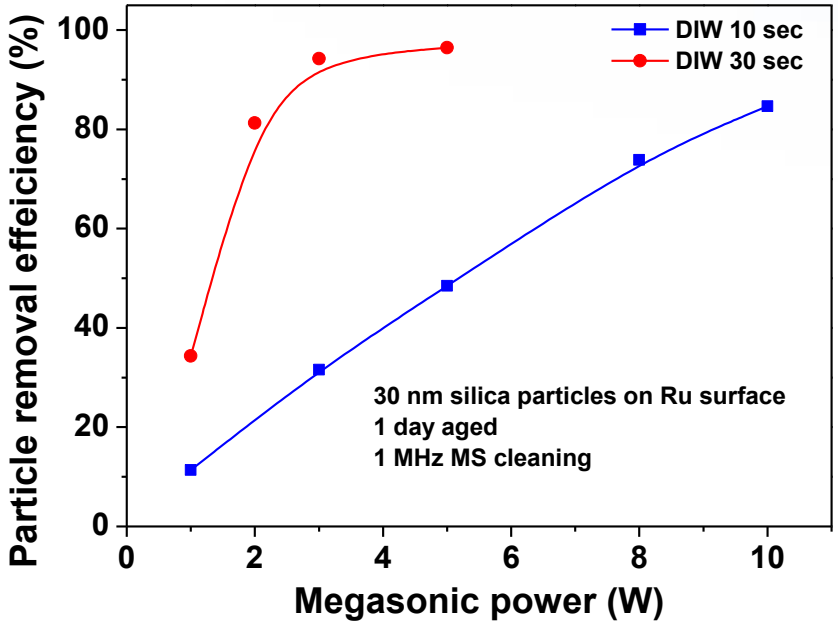
Where, d is diameter of particle
V_p *is fluid velocity at center of particle*

V. Kapila et al., *Proc. of SPIE*, **5992** (2005) 59923X-1

- **Drag force by fluid flow @ 1 MHz MS**
 - → 137 nm silica particle is about **10 times** larger than 30 nm particle
- **Drag force to vdW force ratio**
 - → 137 nm silica particle is about **2 times** higher than 30 nm particle
- **More difficult to remove fine particle**

Result of PRE w/ silica particle size



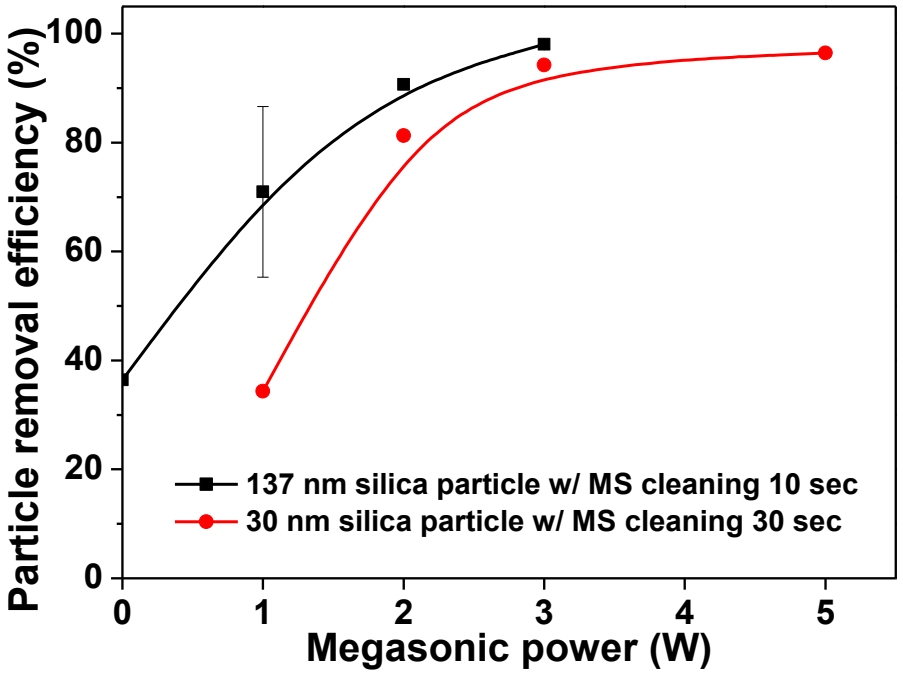


- 137 nm silica particles were almost removed @ 1 MHz 3 W 10 sec
- PRE of 30 nm silica particles was about 80 % despite high MS power 10 W

 → Drag force by acoustic streaming @ 30 nm silica particle is much lower than 137 nm silica particles
- PRE of 30 nm silica particles was over 95 % @ 1 MHz 10 W 30 sec

Result of PRE w/ silica particle size

❖ **Comparison of PRE between 30 nm & 137 nm silica particles**



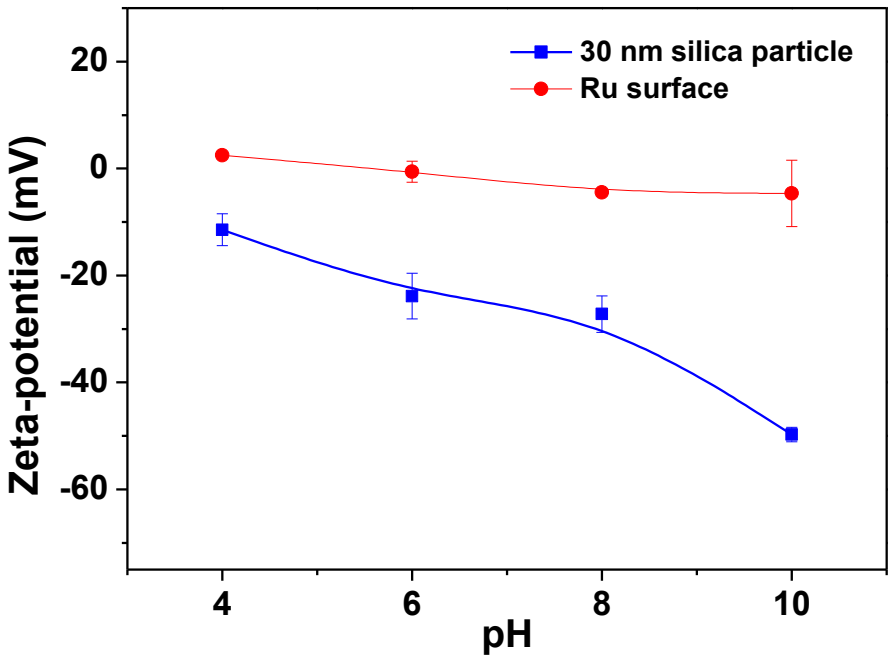
- 137 nm silica particle → 1 MHz MS 3 W 10 sec
- 30 nm silica particle → 1 MHz MS 5 W 30 sec

➢ **More MS power & cleaning process time are required to remove fine particle**

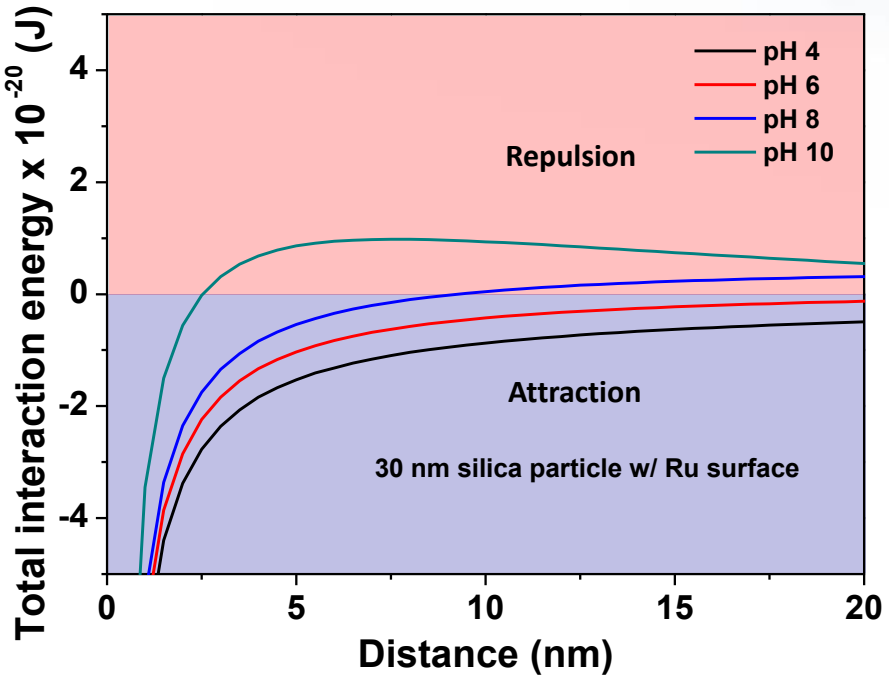
Effect of cleaning solution @ MS cleaning

Total interaction energy between particle and surface

❖ **Zeta-potential of particle & surface**



❖ **Effect of pH on interaction energy**



$$E_{net} = E_{electrostatic} + E_{van\ der\ Waals}$$

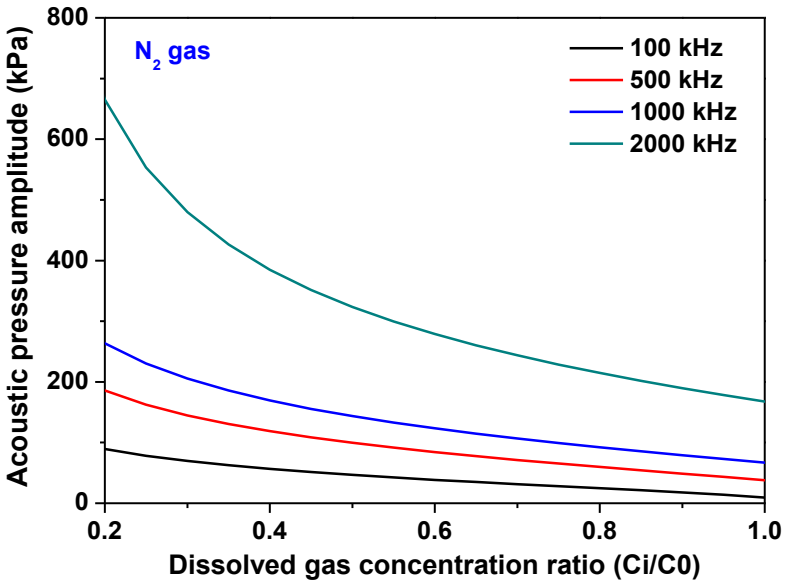
$$E_T = 64\pi R\varepsilon_0\varepsilon\left(\frac{kT}{e}\right)^2 \tanh^2\left(\frac{ze\psi_0}{4kT}\right)e^{-\kappa D} - \frac{AR}{6D}$$

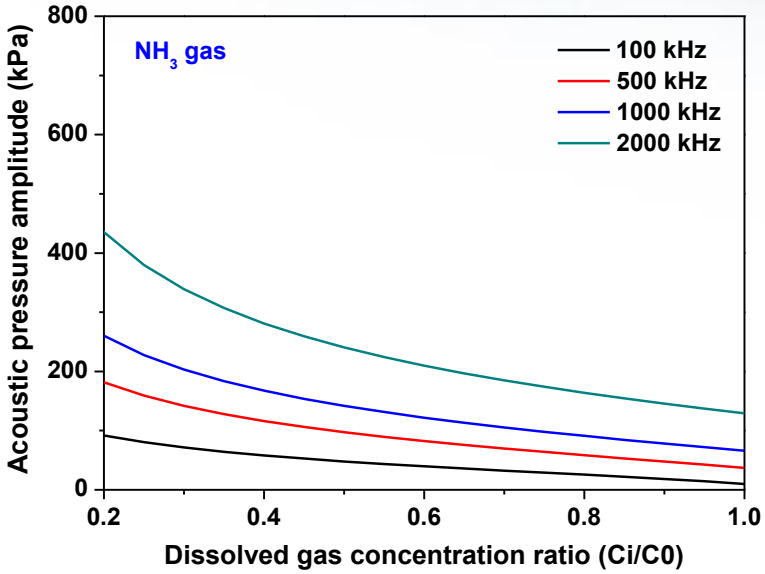
R : Particle radius
ε : Permittivity of medium,
ε_0 : Permittivity of free space
k : Boltzmann constant
T : Absolute temperature

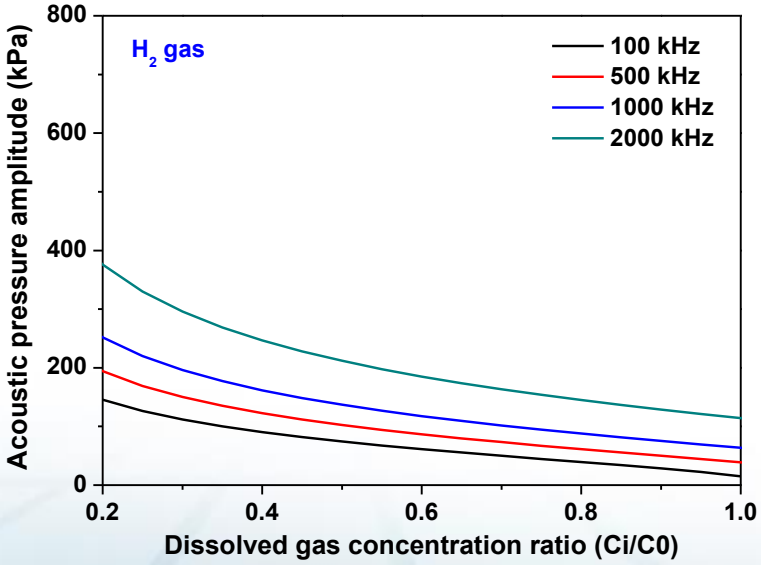
z : Valance number,
κ : Reciprocal of Debye length,
D : Distance between surface and particle
A : Hamaker constant
ψ_0 : zeta potential of particle and surface

- **Zeta-potential is going to negative value @ high pH solution**
- **Interaction energy is repulsion @ high pH solution b/w particles & surface**

Cavitation threshold @ frequency & dissolved gas



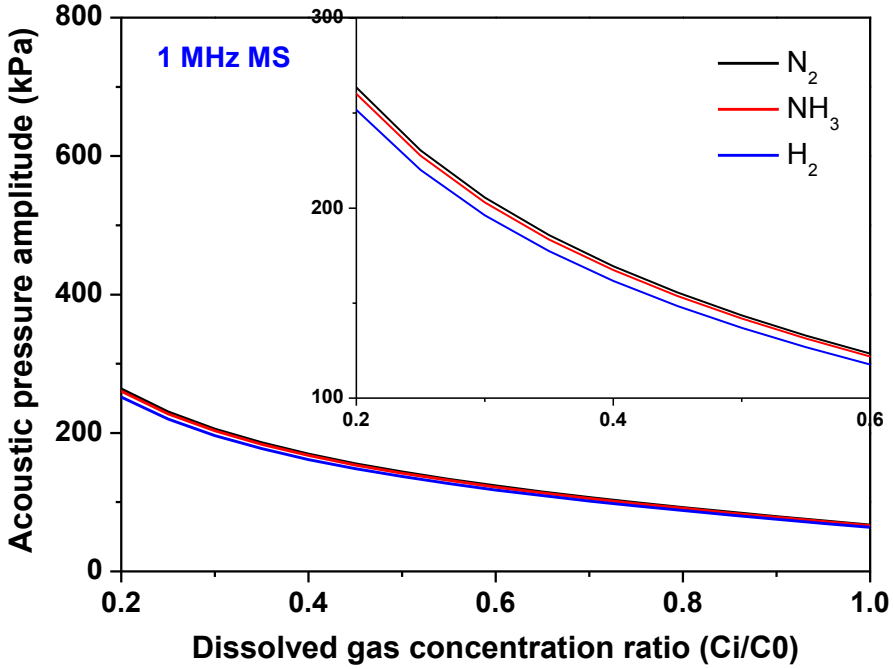


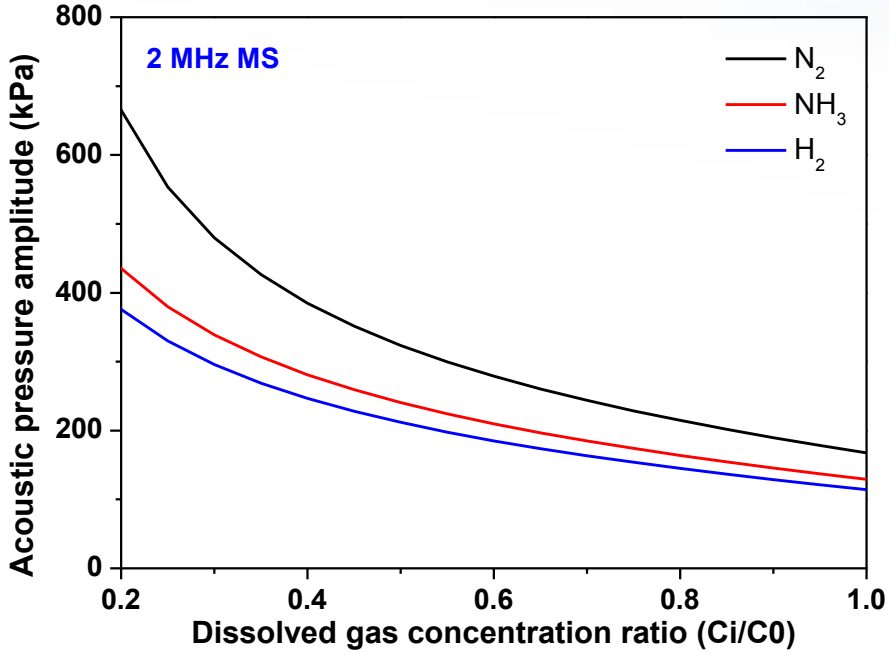


- **Higher frequency of MS ➔ lower cavitation effect & PRE / higher dissolved gas concentration ➔ higher cavitation effect & PRE**

 → Cavitation effect by dissolved gas : H_2 > NH_3 > N_2

Cavitation threshold @ frequency & dissolved gas





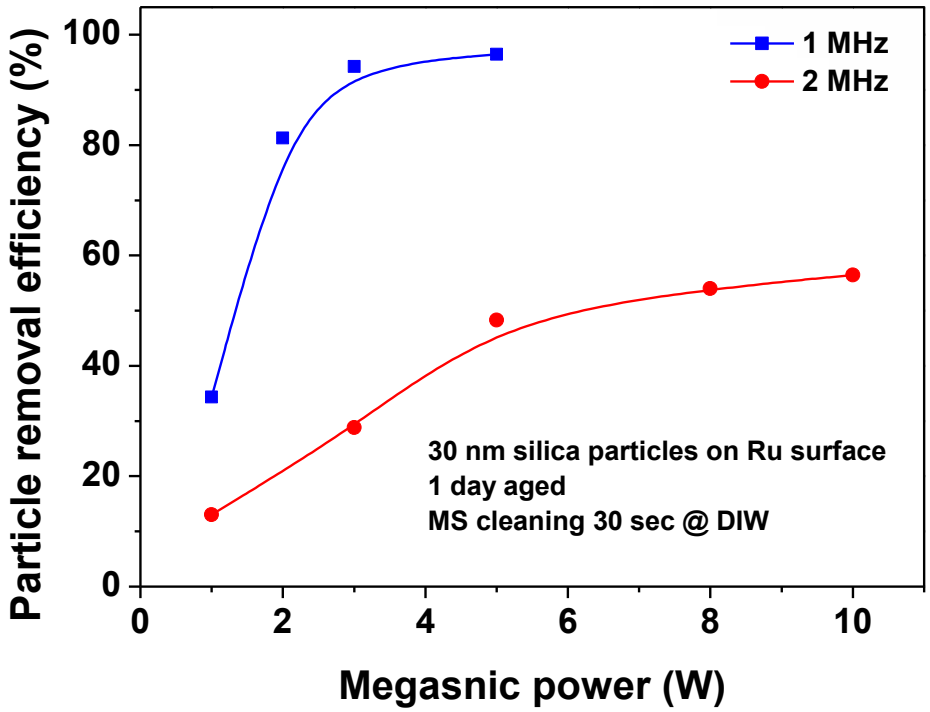
- **Cavitation threshold is lower @ 1 MHz than 2 MHz megasonic**

 ➔ **Small differences in cavitation threshold w/ various dissolved gas @ 1 MHz frequency**

- **There is a large difference in cavitation threshold between gases @ 2MHz frequency**

 ➔ **Lower cavitation effect @ all dissolved gases**

PRE result @ megasonic frequency



- PRE was drastically reduced @ high frequency MS (2 MHz)

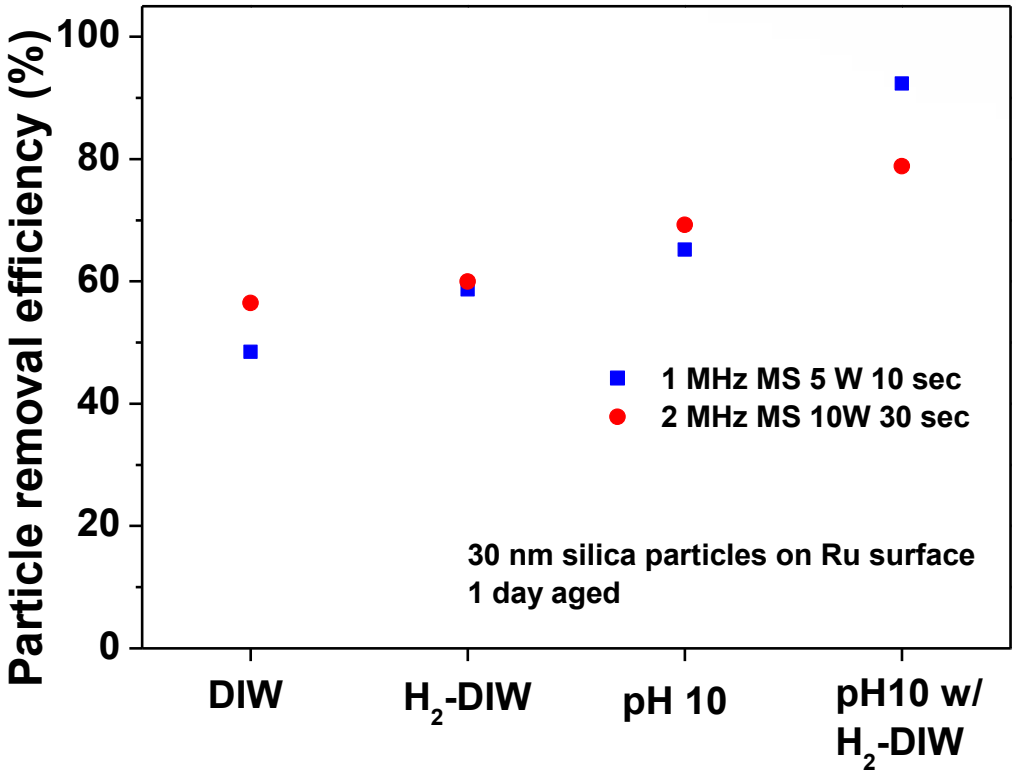
 → Cavitation threshold is much higher than 1 MHz frequency

- Degradation of bubble cavitation effect @ high frequency MS (2 MHz)

 → **Bubble cavitation is a main factor in particle removal**

- **Cleaning solution has to be induced @ high frequency MS cleaning**

Effect of pH & dissolved gas in PRE



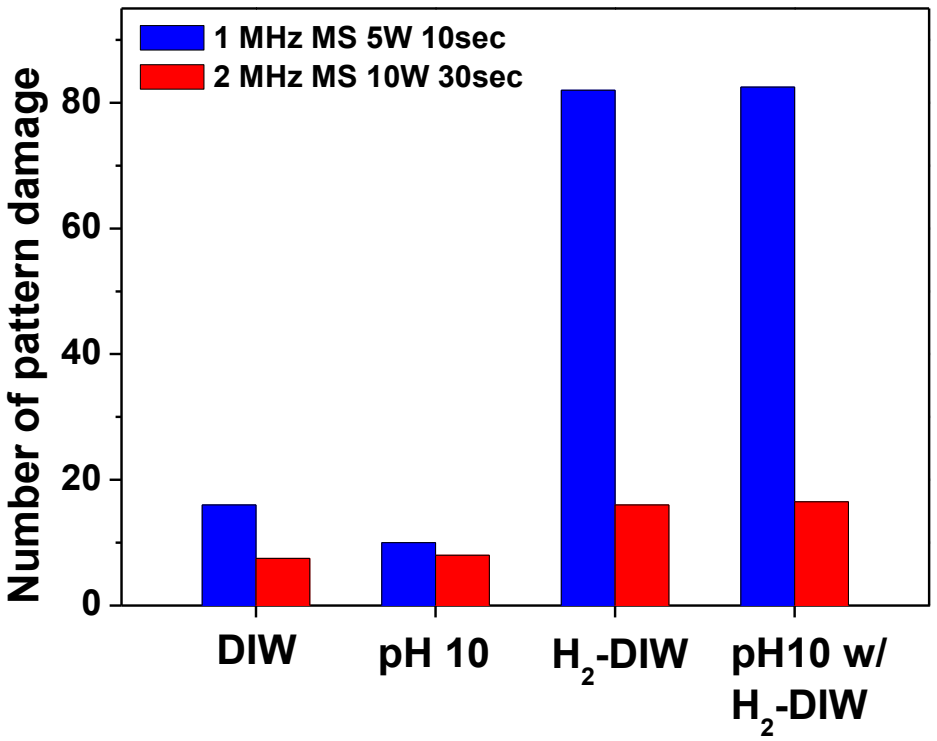
- PRE was improved with addition of NH_4OH (pH 10) and H_2 gas (1 ppm) in DIW

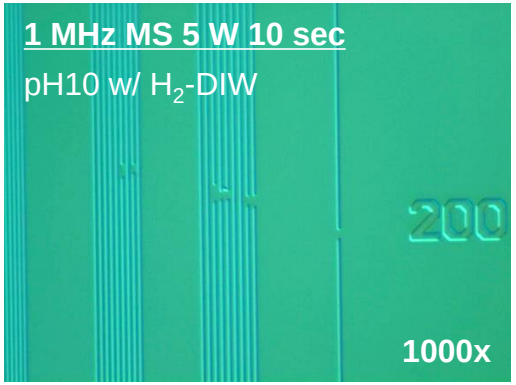
 → **Bubble cavitation effect is more activated by additives**

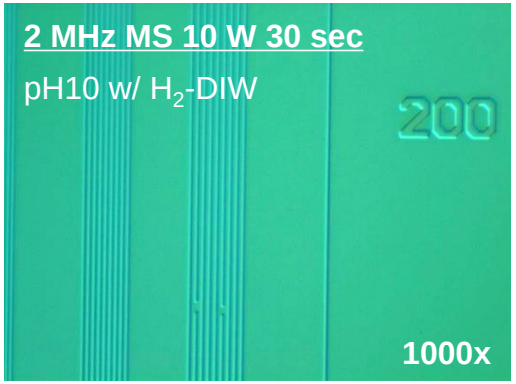
- 2 MHz MS is still lower PRE than 1 MHz MS @ pH10 w/ H_2-DIW solution

 → **Cavitation threshold is higher @ 2 MHz MS**

Result of pattern damage test







- 200 nm PR pattern collapse was higher @ 1 MHz MS cleaning
 → Higher cavitation effect & large bubble size @ 1 MHz MS
- Pattern damage was obviously reduced @ 2 MHz MS despite induced additives
 → **High frequency MS is suitable for damage free cleaning process**

Summary

- **Critical defect size on 16 nm HP node EUV mask**
 - CD variation w/ defect position → Space > Right side > Left side > Absorber
 - **Below 30 nm particles can be occur 10 % CD error**

- **Megasonic cleaning for 30 nm particle removal**
 - More difficult to remove small particle → **Lower drag force than large particle**
 - Cavitation threshold was higher @ 2 MHz MS than 1 MHz MS

 → Additives (NH_4OH & H_2 gas) were induced to increase PRE @ high freq. MS
 - More megasonic power & cleaning process time were required @ 2 MHz MS cleaning

 → **PRE was improved & pattern damage is obviously reduced as compared with 1 MHz MS**

THANK YOU FOR YOUR ATTENTION !!

